

WO 2004/016796

PCT/SE2003/001176

1

METHOD AND DEVICE FOR PRODUCING BIOGASField of the Invention

The present invention relates to a method for producing biogas by anaerobic digestion of organic matter.

The present invention also relates to a device for  
5 producing biogas by anaerobic digestion of organic matter.

Background Art

Digestion of organic waste is utilised in a plurality of processes for reducing volumes of waste and simultaneously producing biogas. In digestion, the organic waste is mixed with a culture of bacteria and is then digested under anaerobic conditions. In digestion, the organic waste is decomposed, thus producing biogas, which  
15 essentially consists of methane and carbon dioxide, and digested sludge.

US 4,652,374 in the name of Cohen discloses a method of digesting organic waste in two steps. The solid organic waste is ground in such a manner that 80% has a particle size of 0.25-1.5 mm. Hydrolysis/acidification takes  
20 place in a first step. The liquid from the first step is separated and supplied to a second step where the main production of methane takes place.

US 4,386,159 in the name of Kanai discloses a method  
25 of digesting organic waste matter with a certain ratio of carbon to nitrogen. The organic waste matter is ground to a juice-like liquid and is then mixed with a bacteria-containing sludge in a tank. Then the digestion is allowed to proceed in the tank without agitation for about  
30 5-7 days.

It is a disadvantage in the above processes that the production of biogas is inefficient and that the biogas therefore will be expensive.

WO 2004/016796

PCT/SE2003/001176

2

Summary of the Invention

An object of the present invention is to provide a method of producing biogas, in which method the above drawbacks are eliminated or significantly reduced, and  
5 thus to provide a method of producing biogas in a more efficient way.

More specifically, the invention provides a method of producing biogas by anaerobic digestion of organic matter, which method is characterised by

10 grinding organic matter,  
mixing the organic matter with a liquid to form a slurry with a dry solids content of 15-45% by weight TS,  
feeding the slurry to a tank reactor and, in the tank reactor, contacting the slurry with biogas-producing  
15 bacteria for digestion under anaerobic conditions, and  
digesting the slurry in the tank reactor at a dry solids content of 5-10% by weight TS while producing biogas.

The invention also relates to a device for producing  
20 biogas by anaerobic digestion of organic matter, said device being characterised in that it comprises a premixing tank for mixing ground organic matter with a liquid to a slurry with a dry solids content of 15-45% by weight TS and a feed pipe for feeding the slurry to a sealable,  
25 essentially gas-tight tank reactor for digesting the slurry at a dry solids content in the tank reactor of 5-10% by weight TS, said tank reactor having an inlet for slurry from the premixing tank and outlets for produced biogas and formed digested sludge.

30 Further advantages and features of the invention will be evident from the following description and the appended claims.

Brief Description of the Drawings

35 The invention will now be described in more detail by way of non-limiting embodiments and with reference to the accompanying drawings.

WO 2004/016796

PCT/SE2003/001176

3

Fig. 1 illustrates a device for producing biogas according to a first embodiment of the invention.

Fig. 2 illustrates a device for producing biogas according to a second embodiment of the invention.

5 Fig. 3 illustrates a device for producing biogas according to a third embodiment of the invention.

Fig. 4 illustrates a device for producing biogas according to a fourth embodiment of the invention.

10 Fig. 5 is a schematic view of a device which has been used in exemplary digestion experiments.

Fig. 6 illustrates the production of biogas per tonne of volatile solids and day in a first exemplary experiment.

15 Fig. 7 shows the contents of volatile fatty acids which have been measured in the first exemplary experiment.

Fig. 8 shows the production of biogas per tonne of volatile solids and day in a second exemplary experiment.

20 Fig. 9 shows the production of biogas per tonne of volatile solids and day in a third exemplary experiment.

#### Detailed Description of the Invention

In the present application, the unit "% by weight TS" relates to the dry solids content (total solids) of a material. The dry solids content of a material is measured according to Swedish standard SS 02 81 13 by the material being weighed before measuring and then being heated at 105°C for 20 h so that water evaporates. The material is then weighed once more. The dry solids content in % by weight TS is then calculated as follows

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$$\% \text{ by weight TS} = \frac{\text{weight after heating at } 105^{\circ}\text{C}}{\text{weight before heating}} * 100\%$$

WO 2004/016796

PCT/SE2003/001176

4

For instance, 90% by weight TS relates to a material where 90% of the original weight of the material remains after heating the material at 105°C for 20 h.

In the present application, the unit "% by weight VS" relates to the content of volatile organic matter of a material, below called the volatile solids content. To determine the volatile solids content, first the dry solids content of the material is determined and then its fixed solids. The fixed solids can be determined according to Swedish Standard SS 02 81 13 by a material which has been evaporated at 105°C for 20 h as stated above being calcined for 2 h at 550°C. The volatile solids content relates in the present application to the dry weight of the material, i.e. the weight after evaporation at 105°C for 20 h, reduced by the fixed solids and then divided by the dry weight of the material, i.e. the weight after evaporation at 105°C for 20 h. The volatile solids content of the material in % by weight VS is thus calculated as follows:

$$\% \text{ by weight VS} = \frac{\text{weight after } 105^{\circ}\text{C} - \text{weight after } 550^{\circ}\text{C}}{\text{weight after } 105^{\circ}\text{C}} * 100\%$$

For instance, a volatile solids content of 85% by weight VS means that 85% of the dry weight of the material, i.e. the weight of the material after heating at 105°C for 20 h, consists of organic, volatile compounds while 15% consists of fixed solids.

The unit "g of volatile solids per day" relates, analogously with the unit % by weight VS, to an amount of volatile organic matter in grams per day as stated above. The amount of volatile organic matter supplied to the reactor, i.e. g of volatile solids, determines how much biogas can be produced since the biogas is produced from the volatile organic matter (and not from the fixed solids or the water contents).

WO 2004/016796

PCT/SE2003/001176

5

By "degree of digestion" is meant, in the present application, the amount of material supplied to a digestion reactor that is converted into biogas in the digestion chamber. If, for instance, 10 g of volatile solids per day is supplied to a reactor in the form of digestible material and the digested sludge removed from the reactor contains correspondingly 2 g of volatile solids per day, the degree of digestion is 80%. The bacteria entrained by removed digested sludge contain some g of volatile solids, and therefore a degree of digestion of 100% according to the above definition cannot be achieved in practice.

In the invention, ground organic matter, which has been mixed with a liquid to a slurry with a high dry solids content, is contacted with biogas-producing bacteria for digestion under anaerobic conditions. Owing to the high dry solids content of the slurry, a certain amount of biogas can be produced in a smaller reactor than has previously been possible. Thus, biogas can be produced at a lower cost by means of the present invention.

It has proved necessary that the organic matter itself should have a high dry solids content for a slurry with a very high dry solids content to be provided.

An example of organic matter which is suited for use in the present invention is dried green matter. In the present invention, green matter relates to plants of the type using photosynthesis for producing the plant matter. The green matter can advantageously consist of various agricultural products, such as ensilage, straw, grain, grain offal, rape, sunflowers, maize, sugar-beets, turnips, cabbage, potatoes, molasses, peas, beans, lentils, flax, lupins and pasture plants, such as lucerne, grass and clover. Agricultural products are often available in large amounts and frequently have a high energy content. Moreover, the agricultural products often have

WO 2004/016796

PCT/SE2003/001176

6

a content of nutrients and trace elements making the produced digested sludge most convenient for use as fertiliser on arable land. A further advantage of the above-mentioned agricultural products is that they do not contain any harmful bacteria. Thus, the heating to at least 70°C for at least 1 h, referred to as sanitation, which is necessary, for instance, in connection with domestic waste and slaughterhouse waste, can be omitted, resulting in reduced production costs. Also products such as lawn waste, straw from edges of roadways, natural hay and leaves, which normally arise in municipal activities, can be used in digestion. To be able to use the above-mentioned examples of green matter, it is in most cases necessary first to dry them to a high dry solids content, since many of the above green matters have an original dry solids content of only 15-35% by weight TS. The drying of the green matter has several advantages. In addition to the fact that a slurry with a higher dry solids content can be introduced into the reactor, it will also be easier to transport and store the green matter. Consequently, the green matter can be harvested and dried at a time of the year when the supply of green matter is good so as then to be digested during an extended period. The dried green matter is also considerably less expensive to transport since a large amount of water has been removed. Green matter should be dried to a dry solids content of at least 50% by weight TS. Drying to at least 70% by weight TS, still more preferred at least 80% by weight TS, has been found to result in still more efficient digestion in the reactor and reduces the amount of water supplied to the reactor.

The digestion in the digestion chamber will be most efficient if the organic matter is ground before being introduced into the digestion chamber. Grinding makes the matter more available to the biogas-producing bacteria and thus accelerates digestion. Green matter can be ground before the above-mentioned drying. Such grinding

WO 2004/016796

PCT/SE2003/001176

7

of "wet" matter, however, is quite difficult to carry out and often results, in particular with green matter having a low dry solids content, in a slurry that is difficult to handle. For this reason, it is often preferred first to dry the green matter and then grind it to the desirable particle size. A suitable particle size of the ground matter from the point of view of digestion has been found to be about 0.5-3 mm, i.e. the major part, at least about 80% by weight, of the matter should have a particle size in this range after grinding. Grinding to smaller particle sizes, for instance below 0.1 mm, increases the dusting problems and increases the consumption of energy in grinding without making digestion significantly quicker. With larger particle sizes of the ground matter, such as larger than 5 mm, the digestion process will be slower, thus requiring a larger reactor. In some cases, for instance with compact green matter such as potatoes, sugar-beets and cabbage, it is convenient to cut the green matter into flakes, for instance flakes with a size of 10-30 mm, before the green matter is dried to achieve maximum efficiency in the drying process. An example of a type of drier which is suitable for drying of green matter is a rotary oven. Drying of green matter may also be preceded by dewatering, which can be carried out, for instance, by means of a filter press, for the purpose of reducing the amount of water that must be removed from the green matter in the actual drying.

It has been found particularly convenient to pelletise the green matter after drying. Pelletising changes the dried green matter into a form which is easy to handle and transport. Thus, green matter can be dried and pelletised locally and transported to large-scale regional plants for producing biogas. A further advantage is that different types of pelletised green matter can easily be dosed in the desired proportions to the reactor to achieve a chemical composition in the reactor which gives the biogas-producing bacteria good conditions for

growth. When using pelletised green matter, it is preferable to grind the pellets before being introduced into the reactor. In the actual pelletising, a certain degree of compacting of the dried green matter is effected.

5 Grinding makes the pelletised matter more available to the biogas-producing bacteria and increases the rate of digestion. Since the pelletised matter has in many cases already been ground before the actual pelletising, a mill for grinding of pellets can be made relatively simple.

10 The above ranges of particle sizes for grinding of the dried organic matter also apply to grinding of pellets.

It has been found possible to produce pumpable slurries with a dry solids content of up to about 35% by weight TS by means of dried organic matter in general.

15 It has surprisingly been found possible to produce pumpable slurries with a dry solids content of up to 45% by weight TS using whole and screened grains of cereals ground to a particle size of about 1 mm. In the present application, cereals relate to grains of wheat, rye,

20 barley, oats, maize and ryewheat. Cereals in the form of whole and screened grains have already in harvesting a dry solids content of about 80-90% by weight TS. Thus, grains of cereals can be used immediately after harvesting and screening for preparing a slurry with a high dry

25 solids content. This means that drying is not necessary, which reduces the cost of producing biogas. In industrial storage of the screened grains of cereals, gentle drying to a dry solids content of about 88-95% by weight TS is required. However, such drying does not require much

30 energy and makes the grains easier to transport and store. The very high dry solids content of the dried grains of cereals in combination with the fact that a pumpable slurry with a very high dry solids content can be prepared from ground grains of cereals results in

35 very little water needing to be supplied to the reactor. Grains of cereals contain mainly starch, which can be quickly decomposed by the biogas-producing bacteria, thus



WO 2004/016796

PCT/SE2003/001176

9

increasing the degree of digestion. The cereals make it possible to increase the supplied amount of organic matter with maintained residence time. A device for digesting grains of cereals can therefore be made very small and efficient. A silo is suitably used to store the grains of cereals. A mill or crusher, which can be of a relatively simple type since the degree of grinding is not very high and the material which is being ground does not cause great wear, is used to grind the grains. The ground grains are mixed in a premixing tank, which may resemble an industrial dough-preparing tank, into a slurry with a high dry solids content, which is then pumped by a pump to a reactor which contains biogas-producing bacteria. The high degree of digestion for organic matter, especially agriculture products in general and grains and grain offal in particular, in the method according to the invention implies that a very large amount of the volatile solids of the slurry supplied to the reactor will be decomposed into biogas. For this reason, the reactor in which digestion takes place will contain digested sludge with a dry solids content of typically 5-10% by weight TS, although the slurry that is supplied to the reactor from the premixing tank has a considerably higher dry solids content. It is advantageous that the digested sludge in the reactor has a considerably lower dry solids content than the slurry supplied since agitation in the reactor is facilitated and the availability of the supplied organic matter to the bacteria is increased, which contributes to the high degree of digestion.

It has been found that also grain offal makes it possible to produce slurry with a very high dry solids content. Grain offal mainly consists of husks and rejected grains from harvesting and threshing of cereals. The grain offal has a dry solids content of 80-90% by weight TS. It has been found particularly convenient to dry, grind and pelletise grain offal or to pelletise the

WO 2004/016796

PCT/SE2003/001176

10

grain offal immediately after drying. These grain offal pellets, which have a dry solids content of about 85-95% by weight TS, make it possible to produce a slurry with a dry solids content of up to 40% by weight TS.

5        It is also possible to produce a slurry with a high dry solids content from different mixtures of grain and dried grain offal.

To achieve the above-mentioned high dry solids contents of the slurry, it is suitable that at least half  
10 of the total dry solids of the slurry originates from grains of cereals and/or dried grain offal. Still more preferred, at least 70% of the total dry solids of the slurry and most preferred at least 85% of the total dry solids of the slurry should originate from grains of  
15 cereals and/or dried grain offal.

It has been found that the produced slurry suitably should have a dry solids content of 15-45% by weight TS, still more preferred 20-40% by weight TS and most preferred 30-40% by weight TS. As mentioned above, it is suitable  
20 able to use pelletised grain offal and still more preferred screened grains of cereals when the highest dry solids contents are to be provided. Compared with digestion of e.g. cow-dung according to prior-art technique, where the dry solids content of the slurry introduced  
25 is only about 6-8% by weight TS, it is possible, in the invention with the same residence time in the reactor, to extract the same amount of biogas from a reactor having only about one-fourth of the volume required in digestion according to prior art.

30        The slurry can be prepared in various ways. A preferred way of preparing a slurry is to mix the organic matter, such as grains of cereals, with water, for instance tap water, lake water, condensate, purified wastewater or some other water-containing liquid which  
35 with regard to biogas production is suitable for supply to the reactor. Thus, also water-containing liquids of little value, or being considered as waste, can thus

WO 2004/016796

PCT/SE2003/001176

11

be used to produce the slurry. According to this method, ground matter is mixed with water in a premixing tank, which is provided with a powerful agitator operating at a low speed. The premixing tank reduces the risk of air  
5 being unintentionally introduced into the reactor and makes it easier to control the amount of matter that is introduced into the reactor. The premixing tank also provides wetting of the organic matter, which results in digestion beginning more quickly in the reactor. A control system is used to achieve the desired dry solids  
10 content of the slurry in the premixing tank. Suitably, a batch method for mixing the slurry is used. The residence time in the premixing tank suitably is relatively short, about 5-50 min. However, in some cases also continuous  
15 methods may be used.

The high dry solids content of the slurry brings several advantages. On the one hand, only little water has to be added. Thus, the consumption of water will be low and the residence time in the reactor will be long,  
20 which results in a good degree of digestion. A small amount of water being added also results in a low cost for heating of added water to the desired digestion temperature. A further advantage of a small amount of water being added is that the produced digested sludge  
25 will have a high dry solids content, which facilitates handling, reduces the cost of transport and increases the value of the digested sludge as fertiliser. The high dry solids content also reduces the pumping work required to pump the slurry into the reactor and makes it possible  
30 to dimension premixing tank, pumps and pipes for smaller flows. An advantage of using essentially pure water when producing the slurry is that the mixing of the slurry can be carried out in an open premixing tank. This makes the tank cheap to manufacture and simple to monitor.

35 Another method of producing a slurry is to discharge digested sludge from the reactor and mix this with the ground organic matter in a premixing tank to form a

WO 2004/016796

PCT/SE2003/001176

12

slurry which is then introduced into the reactor. An advantage of using digested sludge is that no water in addition to the small amount of residual moisture that is present in the organic matter has to be added. Therefore

5 the residence time in the reactor will be long. Since the digested sludge contains bacteria, a certain production of biogas will already take place in the premixing tank, which suitably has a residence time of about 5-50 min. The premixing tank should be an essentially gas-tight

10 container which continuously is vented to prevent explosive gas mixtures from being produced when produced biogas and air accompanying the ground matter are mixed. It is desirable to minimise the energy that is consumed to pump digested sludge to the premixing tank and to pump

15 the slurry prepared from organic matter and digested sludge to the reactor. Of the dry solids content in the thus prepared slurry, about 3-6% by weight TS originates from the digested sludge, and therefore the amount of slurry which, at a given dry solids content of the slurry

20 produced and a given amount of organic matter, must be pumped to the reactor will be slightly greater compared with the above-described mixing with pure water.

A further alternative is to use in the preparation of the slurry a suitable reject water, i.e. a liquid that

25 arises as a residual product in another process. An example of such reject water that can be used is reject water from sludge dewatering in wastewater treatment plants. Such reject water contains, inter alia, potassium and nitrogen that may serve as extra nutriment for the

30 biogas-producing bacteria and, thus, increase the efficiency of the biogas production while at the same time disposing of the reject water which is to be regarded as waste.

It has been found that a slurry with a high dry

35 solids content, which has been prepared from ground agricultural products having a high dry solids content, is very convenient for increasing the biogas production in

WO 2004/016796

PCT/SE2003/001176

13

existing digestion plants. In particular grain offal and whole, screened grains of cereals are very suitable for this purpose. There are a large number of existing digestion plants digesting, for instance, cow-dung, slaughter-  
5 house waste, sorted-out household waste (the part suitable for composting), food waste and sludge from wastewater treatment plants. The purpose of these existing plants is usually to remove waste that is difficult to handle. These plants often digest matter with a low dry  
10 solids content and a low energy content per tonne of waste. As a result, the production of biogas will be small. The formed digested sludge has a low dry solids content and is therefore difficult to handle. According to one aspect of the invention, a slurry with a high dry  
15 solids content is prepared from organic matter, preferably matter which in itself has a high dry solids content, and is supplied to a reactor where organic matter of a different type, for instance cow-dung, is digested. The slurry with a high dry solids content adds very  
20 little liquid to the existent plant. This has the advantage that the residence time in the existing reactor is not reduced significantly. This means that the degree of digestion, i.e. the amount of the supplied matter that is converted during the digestion process, will not  
25 decrease. The supplied slurry, which has a high dry solids content, has a high energy content per kg and will considerably increase the biogas production in the plant. The dry solids content of the removed digested sludge increases owing to more matter being introduced into the  
30 reactor. This makes the digested sludge easier to handle. The introduced organic matter will also increase the nutritive value of the digested sludge, thereby increasing its value as fertiliser. The extra nutriment which thanks to the organic matter is added to the biogas-  
35 producing bacteria can make the bacteria more active by co-digestion, i.e. the nutrients of the digested matters supplement each other, which may result in an increased

WO 2004/016796

PCT/SE2003/001176

14

degree of digestion. The extra equipment that is needed to make an existing digestion process more efficient in the manner described above is simple, especially if the matter which in itself has a high dry solids content, for instance screened grains of cereals, is used. Thus, by means of the invention the biogas production can be increased and the handleability of the digested sludge be simplified and its value increased in an existing digestion plant. It will be appreciated that a slurry with a high dry solids content can also be used in plants which from the beginning are built to digest such a slurry together with other organic matter, which, for instance, can be water treatment sludge, cow-dung or some other waste that is desired to be removed.

In the type of plants where the dried organic waste is used to increase the efficiency of an existing plant, the ground organic matter is mixed with a liquid to form a slurry with a high dry solids content which is then introduced into the reactor. It is preferred that at least 10% by weight of the totally supplied dry solids of the slurry should originate from screened grains of cereals, dried and suitably pelletised grain offal or mixtures of dried grain offal and grain, i.e. for 1 tonne of dry solids supplied to the reactor, at least 100 kg should be dry solids originating from grain or pelletised grain offal. Still more preferred, at least 30% by weight of the totally supplied dry solids should originate from grain or pelletised grain offal. It is desirable to prevent large amounts of slurry or sludge to be circulated in the plant. Circulation of large amounts of slurry causes increased consumption of energy and may also cause interruptions in the digestion process. Thus, it is suitable to produce a slurry having a relatively high dry solids content. Slurry can be produced in many different ways. A preferred method is to remove digested sludge from the reactor and mix it with the ground organic matter in a premixing tank. The slurry formed in the

WO 2004/016796

PCT/SE2003/001176

15

premixing tank is then supplied to the reactor. This has the advantage that no extra water in addition to the small amount of residual moisture that exists in the grain or grain offal is supplied to the reactor. Another  
5 preferred method is to mix the grain or the dried grain offal with the organic matter of a different type, i.e. the cow-dung, the water treatment sludge etc, which is also digested in the reactor. This method is in many cases very cost-efficient since an existing tank can be  
10 used as premixing tank. Also in this method, no extra water is supplied besides the small amount of residual moisture that is present in the grain or grain offal. A further method is to mix the grain or grain offal with pure water in a separate premixing tank. This increases  
15 the amount of water that is supplied to the reactor where the grain or grain offal is digested together with organic matter of a different type, such as cow-dung, water treatment sludge. Grain and dried and pelletised grain, however, has the advantage that a slurry with a very high  
20 dry solids content can be produced. The small amount of water which will then be required can often be accepted. In the cases when pure water must, for some reason, be supplied to the reactor anyway, this water can suitably be used to prepare the slurry with a high dry solids  
25 content.

A particularly suitable method of using grain or grain offal in a process where another material is digested aims at controlling the biogas production. Momentary adding of a certain amount of grain and/or  
30 grain offal will increase the biogas production with a very short time delay. When the demand for biogas increases in an expected or unexpected manner, grain or grain offal can thus be supplied to a reactor digesting, for instance, sewage sludge in order to meet the  
35 increased demand for biogas. Owing to grain and grain offal being easily decomposable, the biogas production will increase very quickly, thus making it possible to

WO 2004/016796

PCT/SE2003/001176

16

meet the increased demand with a small waste of time. An example is a plant digesting sewage sludge and producing biogas which is used in local busses. On weekdays, the demand for biogas is great and therefore grain as well as  
5 sewage sludge is supplied to the reactor on weekdays. On the last weekday before a weekend, the supply of grain is stopped and the biogas production decreases quickly, typically after 4-24 h, to a low level corresponding to the biogas production that is consumed by the local  
10 busses during the weekend. Just before the end of the weekend, the supply of grain is started again, so that the biogas production again reaches the level which is suitable on weekdays. In this way, a plant is provided, which continuously takes care of and digests sewage  
15 sludge and which in periods with a great demand for biogas also digests grain or grain offal.

Digestion is conveniently carried out as a continuous or semicontinuous process by means of a tank reactor which will be described in more detail below, or by  
20 means of a tube reactor which is also called plug flow reactor. At a first end of the tube reactor, for instance grain and a bacteria culture, which for instance can be present in the form of recirculated digested sludge, are introduced, digested sludge and biogas being discharged  
25 at a second end of the tube reactor, said second end being located downstream of the first end of the tube reactor. The method can also be carried out in a batch reactor.

For the anaerobic digestion to function, air is  
30 not allowed to come into contact with the sludge during digestion. A reactor for use in the method according to the invention must thus be air-tight. The reactor is provided with an inlet for slurry with a high dry solids content and outlets for digested sludge and biogas, said  
35 inlet and outlets being designed so that no air can enter the reactor.



WO 2004/016796

PCT/SE2003/001176

17

Grain and dried grain offal are digested suitably for an average residence time of about 5-100 days, preferably about 40-60 days. A longer residence time improves the degree of digestion but at the same time the quantity of the slurry with a high dry solids content that can be treated is reduced.

Digestion takes place at a temperature of 30-65°C. A higher temperature usually results in quicker digestion. At the same time the heating costs increase and the time that is available for taking care of any problems in the process is reduced. Certain bacteria cultures also have a production maximum which is lower than the above-mentioned upper temperature range. It has therefore been found that a temperature in the range 36-40°C is particularly preferred in the present invention. It is suitable to make an adjustment between residence time, temperature and degree of digestion and use the most economical combination of these factors.

In digestion in a tank reactor, the dry solids content of the digested sludge in the reactor is suitably about 4-30% by weight TS, preferably about 5-10% by weight TS. In an agitated and continuously operating tank reactor, the digested sludge removed from the reactor will have essentially the same dry solids content as the digested sludge in the reactor. Supply of new slurry to the tank reactor is thus made continuously, i.e. as an even inflow, or semicontinuously, i.e. in small portions, preferably from a premixing tank. Removal of sludge from the tank reactor can be effected continuously, i.e. as an even outflow, or semicontinuously, i.e. in small portions.

When starting the process, an active culture of bacteria is usually introduced into the reactor. This culture of bacteria may consist of, for instance, digested sludge from a parallel digestion plant, digested sludge from a municipal wastewater treatment plant or cow-dung. As the culture of bacteria grows, an increasingly greater

WO 2004/016796

PCT/SE2003/001176

18

amount of the slurry with a high dry solids content can be supplied to the reactor. Too quick an increase of the amount of supplied slurry is prevented by measuring at short intervals the content of volatile fatty acids in the digested sludge and ensuring that the content of volatile fatty acids is kept at a desirably low level by regulating the supply of dried matter.

The method according to the invention can be carried out in a plurality of reactors connected in series. However, it is particularly advantageous to carry out the anaerobic digestion in a single step since this saves equipment and maintenance costs.

#### Description of Preferred Embodiments

Fig. 1 shows a first embodiment of a device 1 for producing biogas. The device 1 has a container in the form of an essentially gas-tight reactor 2. The reactor 2 has an inlet 4 for organic matter, an outlet 6 for produced biogas and an outlet 8 for formed digested sludge. An agitator 10 keeps the matter in the reactor agitated. Grain which has been dried to a dry solids content of 92% by weight TS is supplied from a storage silo (not shown) through a feed pipe 12 to a mill 14. In the mill 14, the grain is ground to an average particle size of about 1 mm. The ground grain is supplied through a feed pipe 16, which may consist of, for instance, a screw conveyor, to a premixing tank 18. The premixing tank 18, which is an open tank, has a low speed agitator 20. The agitator 20 is a scraper-type agitator and may conveniently resemble the agitators that are used in the baking industry for preparing dough. A water supply pipe 22 is arranged to supply essentially pure process water to the premixing tank 18. A control system 24 is arranged to batch feed water through the pipe 22 and ground grain through the pipe 16 to the premixing tank 18 in such proportions that a dry solids content of 35% by weight TS is obtained in the premixing tank 18. Use is suitably made

WO 2004/016796

PCT/SE2003/001176

19

of a weighing cell (not shown) which is arranged under the premixing tank 18, to control the supply of water and grain to the premixing tank 18. When a slurry of grain and water has been mixed to an even consistency in the premixing tank 18, the slurry is pumped through a pipe 26 by a pump 28 to the inlet 4 of the reactor 2 and into the reactor 2. To obtain an even liquid volume in the reactor 2, a corresponding amount of digested sludge is pumped out through the outlet 8. The reactor 2 thus is a continuously or semicontinuously operating, agitated tank reactor which contains digested sludge with a dry solids content of about 5-10% by weight TS.

Fig. 2 shows a different embodiment of the invention in the form of a device 100. The device 100 has an essentially gas-tight container in the form of a reactor 102 which has an inlet 104 for organic matter, an outlet 106 for produced biogas, an outlet 108 for formed digested sludge and an agitator 110 of essentially the same design as those shown in Fig. 1.

Dried and pelletised grain offal is passed from a storage silo (not shown) through a feed pipe 112 to a mill 114. In the mill 114, the pellets are ground to an average particle size of about 1 mm. The ground pellets are fed through a feed pipe 116 to a premixing tank 118. The premixing tank 118, which is an essentially gas-tight container, has a low speed agitator 120. A liquid supply pipe 122 is arranged to supply, by means of a pipe 123 and a pump 125, digested sludge from the reactor 102 to the premixing tank 118. A control system 124 is arranged to batch feed digested sludge through the pipe 122 and ground pellets through the pipe 116 to the premixing tank 118 in such proportions that a dry solids content of 35% by weight TS is obtained in the premixing tank 118. When a slurry prepared from pellets and digested sludge has been mixed to an even consistency in the premixing tank 118, the slurry is pumped through a pipe 126 by a pump 128 to the inlet 104 of the reactor 102 and into the

WO 2004/016796

PCT/SE2003/001176

20

reactor 102. To obtain an even liquid volume in the reactor 102, a corresponding amount of digested sludge is pumped out through the outlet 108. In the premixing tank 118, a certain amount of biogas will be produced during the mixing process. A gas pipe 130 conducts this gas, which consists of a mixture of produced biogas and the air which has unintentionally been supplied through the feed pipe 116, to a biofilter (not shown) which decomposes methane and odorous gases. If it is necessary to be able to keep the dry solids content in the reactor 102 at a desirable level, pure process water can be supplied to dilute the sludge in the reactor. This process water can either be supplied to the premixing tank 118 through a pipe 132 or directly to the reactor 102 through a pipe 134.

Fig. 3 is a schematic view of a third embodiment of the invention in the form of a device 200. The pumps and agitators are not shown in Fig. 3, but it will be appreciated that such components are used in essentially the same way as illustrated in Figs 1 and 2. The device 200 digests a mixture of cow-dung, which is supplied to a mixing tank 240 through a pipe 242, and slaughterhouse waste, which is supplied to the mixing tank 240 through a pipe 244. The mixing tank 240 is a closed tank which by means of a gas pipe 243 is vented to a biofilter (not shown) which decomposes methane and odorous gases. The mixture obtained in the mixing tank 240 is passed through a pipe 246 to a sanitation tank 248 where the mixture is heated to at least 70°C for at least 1 h for the purpose of killing harmful bacteria. The sanitised mixture, which has a dry solids content of about 4-12% by weight TS, is passed through a pipe 250 from the sanitation tank 248 to a reactor 202, which is of a type similar to the reactor 102 as described above and thus has, among other things, an outlet 206 for produced biogas and an outlet 208 for formed digested sludge.

WO 2004/016796

PCT/SE2003/001176

21

With a view to improving the biogas production in the device 200, dried grain is fed through a feed pipe 212 to a mill 214 where the grain is ground to an average particle size of about 1 mm. The ground grain is fed  
5 through a feed pipe 216 to a premixing tank 218 which is of essentially the same type as described above regarding the premixing tank 218. A liquid supply pipe 222 is arranged to feed digested sludge from the reactor 202 to the premixing tank 218. A control system 224 is arranged  
10 to batch feed digested sludge through the pipe 222 and ground grain through the pipe 216 to the premixing tank 218 in such proportions that a dry solids content of 35% by weight TS is obtained in the premixing tank 218. When a slurry prepared from grain and digested sludge has been  
15 mixed to an even consistency in the premixing tank 218, the slurry is pumped from the premixing tank 218 to the reactor 202 through an inlet 204. A gas pipe 230 conducts gas, which is generated in the mixing in the premixing tank 218, to a biofilter (not shown) which decomposes  
20 methane and odorous gases.

Fig. 4 shows schematically a fourth embodiment of the invention in the form of a device 300. The pumps and the agitators are not shown in Fig. 4, but it will be appreciated that such components are used in essentially  
25 the same way as illustrated in Figs 1 and 2. The device 300 digests cow-dung and meat waste. The cow-dung and the meat waste are fed through a pipe 322 and a pipe 323, respectively, to an essentially gas-tight tank 318 and are mixed.

30 With a view to improving the biogas production in the device 300, dried and pelletised grain offal is fed through a feed pipe 312 to a mill 314 where the pellets are ground to an average particle size of about 1 mm. The ground pellets are fed through a feed pipe 316 to the  
35 tank 318, which in the device 300 thus is used as premixing tank and is of essentially the same type as described above regarding the premixing tank 118. A certain amount

WO 2004/016796

PCT/SE2003/001176

22

of biogas will be produced in the premixing tank 318 in the mixing process. A gas pipe 330 conducts gas, which consists of a mixture of produced biogas, air unintentionally supplied through the feed pipe 316 and gases generated by the cow-dung and the meat waste, from the tank 318 to a biofilter (not shown) which decomposes methane and odorous gases. A control system 324 is arranged to batch feed cow-dung and meat waste through the pipes 322, 323 and ground pellets through the pipe 316 to the premixing tank 318 in such proportions that a dry solids content of 35% by weight TS is obtained in the premixing tank 318. When ground pellets, cow-dung and meat waste have been mixed to a slurry with an even consistency in the premixing tank 318, this slurry is pumped from the premixing tank 318 through a pipe 326 to a sanitation tank 348 where the slurry is heated to at least 70°C for at least 1 h for the purpose of killing the harmful bacteria that may exist in the slaughterhouse waste. The sanitised slurry is pumped from the sanitation tank 348 through an inlet 304 into a reactor 302 which is of a type similar to the reactor 2 as described above and thus has, inter alia, an outlet 306 for produced biogas and an outlet 308 for formed digested sludge.

It will be appreciated that many variations of the embodiments described above are feasible within the scope of the invention as defined by the appended claims.

#### Example 1

In a digestion experiment involving grain, an experimental device 400 which is shown in Fig. 5 was used, said device 400 having a gas-tight glass reactor 402 with a volume of 5 l. The liquid volume in the reactor 402 was kept constant at 3 l. A propeller agitator 410 (with a speed of 300 rpm) was used to achieve complete agitation in the reactor 402. A pipe 406 passed generated gas from the reactor 402 to a gas meter 412 measuring the volume of generated gas. A tight glass feed-through 404 was used for

batch supply of grain and intermittent removal of formed digested sludge. A tempered space (not shown) was used to keep the temperature in the glass reactor 402 at 37°C.

When starting the experiment, 3 l of digested sludge from a full-scale digestion plant was introduced into the reactor 402. The sludge that was digested in the full-scale plant was of the origin that is evident from Table 1.

Supplied product	Unit by volume
	% by volume
Cow-dung	5.4
Slaughterhouse waste	72.7
Others*	21.9
Total:	100

\* "Others" includes above all waste from food production and waste from large-scale kitchens.

Table 1. Origin of materials in full-scale plant.

When starting the experiment, the reactor 402 thus contained active digested sludge including an active culture of biogas-producing bacteria.

10 g grain was charged to the reactor 402 daily. The grain consisted of 50% rye and 50% wheat and was present in the form of whole and screened grains. The grain was ground in a laboratory mill of the type Retsch Mühl type SR2 delivered by Retsch GmbH, DE, to a particle size of about 1 mm. The dry solids content of the ground grain was 91.6% by weight TS and the volatile solids content was 96.7% by weight VS. Thus, each day 8.68 g of volatile solids was charged, which corresponded to about 3 g of volatile solids per litre of reactor liquid and day. The ground grain was mixed with 18 ml water to a substrate mixture with a dry solids content of 35% by weight TS and a volume of 25 ml. For practical reasons, it was necessary to dilute the substrate mixture with digested sludge to be able to introduce it into the reactor 402 through

the tight glass feed-through 404 by means of a syringe. For this reason, 100 ml digested sludge was removed daily. 75 ml of this digested sludge was mixed with the substrate mixture and introduced together with the substrate mixture into the reactor 402. The remaining 25 ml of the digested sludge was rejected to keep the volume in the reactor 402 constant. The residence time in the reactor thus was 120 days with the charging stated above.

Fig. 6 shows the production of biogas in the unit  $\text{Nm}^3$  of gas per added tonne of volatile solids and day as a function of the number of days after start. As appears from Fig. 6, the production is first somewhat irregular. From day 50, the system is balanced. As appears from Fig. 6, the average production of biogas from day 50 to day 70 is about  $700 \text{ Nm}^3$  of biogas per tonne of volatile solids and day, " $\text{Nm}^3$ " relating to  $\text{m}^3$  of gas at  $0^\circ\text{C}$  and  $1.013 \cdot 10^5 \text{ Pa}$  and "tonne of volatile solids per day" relating to the amount of volatile solids that is charged daily. Calculated on the charged grain, the average production was  $616 \text{ Nm}^3$  of biogas per tonne of grain and day. Calculated on the dry solids content of charged grain, the average production was  $673 \text{ Nm}^3$  of biogas per tonne of dry solids and day. The produced biogas was collected at regular intervals and analysed with respect to methane content. In stable production, the methane content was 49-51 %. Fig. 6 also shows the pH of the reactor liquid in the experiment. Except for certain disturbances, the pH was relatively stable in the range 7.3-7.5. The removed digested sludge had a dry solids content of 6.6% by weight TS and a volatile solids content of 89.4% by weight VS, corresponding to a degree of digestion of 83%.

Fig. 7 shows the content of volatile fatty acids in the digested sludge as a function of the number of days from start. As is evident, the contents of the various fatty acids vary considerably during the first 50 days of the experiment. In days 50-70, the contents are stabilised. This may be explained by the fact that it



takes time for the culture of bacteria, originating from digestion of essentially animal waste, to adapt to the grain. There was also some experiment-related problems at the beginning of the experiment. Round day 70, the contents of all fatty acids are low, indicating that the digestion process is efficient and operates in a stable manner.

Example 2

A device 400 of the type described above was used for the experiment. At the start of the experiment, 3 l of digested sludge was charged from the above-mentioned full-scale plant. The origin of the digested sludge is thus evident from Table 1 above.

The substrate that was supplied to the reactor 402 consisted of grain and pasture plants. The grain consisted of 50% rye and 50% wheat and was present in the form of whole and screened grains. The grain was ground in the above-mentioned laboratory mill to a particle size of about 1 mm. The dry solids content of the ground grain was 91.6% by weight TS and the volatile solids content was 96.7% by weight VS. The pasture plants consisted of a mixture of clover and grass and had a dry solids content of 30.8% by weight TS and a volatile solids content of 92.2% by weight VS.

Four days a week, only ground grain was supplied to the reactor 402. The supply of grain amounted to 11.1 g, corresponding to 10 g of volatile solids. The supply of grain was carried out by mixing grain and water to a dry solids content of 35% by weight TS similarly to the way described in Example 1.

The remaining three days a week, both grain and pasture plants were added as follows: 300 ml digested sludge was removed from the reactor 402 and mixed for about 1 min with 25 g pasture plants, corresponding to 7 g of volatile solids, in a food processor. 3.3 g ground grain, corresponding to about 3 g of volatile solids, was mixed

WO 2004/016796

PCT/SE2003/001176

26

with 6 ml water to a mixture with a dry solids content of 35% by weight TS. This mixture of grain was added to the mixture of pasture plants in the food processor, after which the entire mixture was introduced into the reactor 402 through the glass feed-through 404. A certain amount of digested sludge, about 20 ml, was removed and rejected each day to keep the volume in the reactor constant. Calculated as an average during the entire experiment, thus 10 g of volatile solids was added per day, corresponding to 3.3 g of volatile solids per litre of reactor liquid and day, of which 7 g of volatile solids per day was grain and 3 g of volatile solids per day was pasture plants. The residence time in the reactor 402 was about 150 days.

Fig. 8 shows the production of biogas per day in the unit  $\text{Nm}^3$  of biogas per added tonne of volatile solids and day as a function of the number of days after start. As appears from Fig. 8, the system has still not after 40 days been stabilised. However, it may be read from Fig. 8 that the average production of biogas from day 32 to day 39 was about  $561 \text{ Nm}^3$  biogas per tonne of volatile solids and day. Calculated on the charged grain and pasture plants, the average production was  $505 \text{ Nm}^3$  of biogas per tonne of grain+pasture plants and day. Calculated on the dry solids content of the charged grain and pasture plants, the average production was  $541 \text{ Nm}^3$  biogas per tonne of dry solids and day. The produced biogas was collected at regular intervals and analysed with respect to methane content. At the end of the experiment, the methane content was 50-51%. Fig. 8 also shows the pH of the reactor liquid during the experiment. Except for certain disturbances, the pH was relatively stable in the range 7.5-7.8. The removed digested sludge had a dry solids content of 6.3% by weight TS and a volatile solids content of 83.9% by weight VS. The contents of volatile fatty acids were approximately the same as in Example 1,

WO 2004/016796

PCT/SE2003/001176

27

although stability had still not been achieved after 40 days.

As is evident from the results in Example 2, also such a moderate addition as 30% (calculated on the charged amount of volatile solids per day) of non-dried pasture plants strongly deteriorates the gas production in the reactor compared with the case involving digestion of grain only, like in Example 1. This may be caused by the fact that the removal of as much as 300 ml digested sludge to be mixed with pasture plants in the food processor had interfered with the process in the reactor.

Example 3

A device 400 of the type as described above was used for the experiment. At the start of the experiment, 3 l of digested sludge from the above-mentioned full-scale plant was charged. The origin of the digested sludge is thus apparent from the Table 1 above.

Each day, 10 g of pelletised grain offal was charged to the reactor 402. The grain offal essentially consisted of husks, stems and rejected grains. The grain offal had first been dried in an oven and then pelletised in a pelletising machine. The pellets were ground in the above-mentioned laboratory mill to a particle size of about 1 mm. The dry solids content of the ground pellets was 88.6% by weight TS and the volatile solids content was 96.5% by weight VS. Thus, each day 8.55 g of volatile solids was charged, corresponding to barely 3 g of volatile solids per litre of reactor liquid and day. The ground pellets were mixed with 18 ml of water to a substrate mixture with a dry solids content of 35% by weight TS and a volume of 25 ml. For practical reasons, it was necessary to dilute the substrate mixture to be able to introduce it into the tight glass feed-through 404 by means of a syringe. For this reason, 100 ml digested sludge per day was removed. 75 ml of this digested sludge was mixed with the substrate mixture and introduced toge-

ther with the substrate mixture into the reactor 402. The remaining 25 ml of the digested sludge was rejected to keep the volume in the reactor 402 constant. The residence time in the reactor was 120 days with the above-described charging.

Fig. 9 shows the production of biogas per day in the unit  $\text{Nm}^3$  of biogas per added tonne of volatile solids as a function of the number of days after start. As appears from Fig. 9, the production was first somewhat irregular. From day 50, the production became stable. As appears from Fig. 9, the average production of biogas is from day 50 to day 70 about  $722 \text{ Nm}^3$  of biogas per tonne of volatile solids and day. Calculated on the charged pellets, the average production was  $616 \text{ Nm}^3$  of biogas per tonne of pellets and day. Calculated on the dry solids content of charged pellets, the average production was  $697 \text{ Nm}^3$  of biogas per tonne of dry solids and day. The produced biogas was collected at regular intervals and analysed with respect to methane content. In stable gas production, the methane content was 51-53%. Fig 9 also shows the pH of the reactor liquid during the experiment. Except for certain disturbances, the pH was relatively stable in the range 7.5-7.7. The removed digested sludge had a dry solids content of 6.8% by weight TS and a volatile solids content of 85.9% by weight VS. The contents of fatty acids were generally lower than in Example 1, which emphasises that the operation in the experiment was very stable.

Thus, it is evident from Fig. 9 that the production of biogas was essentially as great as in Example 1. In Table 2 below, the production of biogas in the three experiments has been compiled. As is evident, a considerably lower gas production was achieved in the experiment in Example 2, where pasture plants were added, than in the experiments in Examples 1 and 3.

WO 2004/016796

PCT/SE2003/001176

29

Example	Substrate	Biogas production
		Nm <sup>3</sup> biogas/tonne of volatile solids and day
1	Grain	700
2	Grain+pasture plants	561
3	Pelletised grain offal	722

Table 2. Compilation of the results of the experiments

It has been found in the experiments that the substrate mixtures prepared from ground grain and pelletised grain offal, respectively, and with a dry solids content of 35% by weight TS were definitely pumpable although they could not be injected into the glass reactor 402 by means of a syringe. Pumpable substrate mixtures with a dry solids content of up to 42% by weight TS could be provided by means of ground grain.